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Experimental results of propagating up to 400 kA of relativistic electron beams ($\sim$ 1 MeV) over a distance of 64 cm in a tightly focused mode are reported. Efficient transport ($>$ 80%) was observed when a channel of plasma containing enough current to confine the hot electrons was used. Theory of the flow includes return current effects, and is in good agreement with experimental results. The theory is used to predict limits of this technique.

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PROPAGATION OF RELATIVISTIC ELECTRON BEAMS
IN CURRENT-CARRYING PLASMA CHANNELS

I. INTRODUCTION:

The propagation of relativistic electron beams in plasma channels has, in the last decade,[1-7] received considerable interest due to its applications for energy transfer and pellet fusion. A rough division of this effort may be made by characterizing the electron beam as hot or cold. In both cases, the relativistic electron beam propagates in a plasma having a self-consistent azimuthal magnetic field which confines the electrons radially. The necessary magnetic field for hot beam (electrons injected with a large mean angle) propagation is given by Alfvén's treatment of electron orbits which yields the condition that the net current inside the beam radius must be in the same direction as the beam current and nearly equal to the Alfvén current for the energy of the relativistic electrons

$$I_{CH} \simeq I_{\alpha} = \frac{mc^3}{e} \left(\gamma^2 - 1 \right)^{\frac{1}{2}} = 17(\gamma^2 - 1)^{\frac{1}{2}} \text{ kA} \qquad (1)$$

On the other hand, for relatively cold beams (mean angle of injection, $\theta \ll 1$), the same treatment indicates that the current needed is only

$$I_{CH} \simeq (1 - \cos \theta) \, I_{\alpha} \simeq \frac{1}{2}\theta^2 I_{\alpha} \qquad (2)$$

In order to propagate 1 MeV electrons with a 10° mean injection angle, one needs only about 1 kA of net current in the channel compared to the 50 kA of net current needed for hot beam propagation.

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For typical beam currents of a few hundred kiloamperes injected into plasmas at densities of the order of 10^{18} cm^{-3}, the return current induced in the plasma is nearly equal to the primary beam current leaving net currents of the order of 1% of the beam currents. The remainder of the return current flows outside of the beam radius. The resulting net current of a few kiloamperes within the beam radius is sufficient to propagate relatively cool beams (as discussed above) but is insufficient for the propagation of a hot beam. Other means for providing the needed net current must therefore be utilized for hot beam propagation. Historically, these included Z-pinch plasmas[5], and axial discharges via exploding wires.[6,7]

In the present work, we describe an experimental and theoretical study into the physics of the propagation of hot beams in plasma discharges driven by an exploding wire. Our work is an extension of previous work at Sandia[6,7] into a regime of higher beam currents (up to 300 kA injected) and investigating the effect of channel current and diode voltage on beam propagation. In the theoretical study, we investigate the effects of scattering and axial electric fields on electron orbits as well as the limitations on the maximum beam current and beam current density that can be propagated.

II. EXPERIMENTAL APPARATUS AND OBSERVATIONS:

The experimental results of the present work were obtained on the GAMBLE I (800 kV, 220 kA, 80 ns FWHM) and GAMBLE II (1000 kV, 420 kA, 50 ns FWHM) electron beam facilities. A schematic of the experimental apparatus is shown in Figure 1. An 84/39 mm (O.D./I.D.)

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was used. The anode was a 1.5 mm thick brass plate with a 20 mm diameter

hole on axis. The hole was beveled at 30° on the cathode side and sanded

to provide a smooth transition region for the radial electron flow. The

hole was covered with a 25 µm titanium foil which was both ground plane

and vacuum window. Immediately behind this was mounted a 20 µm aluminum

foil on which a 51 µm tungsten wire was affixed. The wire was stretched

in air from the center of the foil through the aluminum target plate,

located 30 to 64 cm away, to a 56 µf, 2.4 µh (total circuit inductance),

20 kV capacitor bank. A "squirrel cage" of aluminum rods and rings

served as a symmetric current return for the channel current. This

bank could drive a peak current of 50-80 kA (occurring approximately

15 µs into the pulse) in an air plasma surrounding the wire.

The experimental diagnostics included diode voltage and current

monitors; time integrated hard x-ray pinhole cameras looking at the

anode, plasma channel, and target; open shutter visual photography

of the channel; time resolved, calibrated x-ray p-i-n diode detectors;

and $\int \dot{B}_\theta$ and Rogowski coils monitoring the channel current. In addition,

a depth dose stack utilizing thermoluminescent detectors were used to

obtain the peak kinetic energy of the transported electrons.

Streak camera measurements of the plasma channel over the times

of interest allowed us to determine the channel radius at the time of

beam injection. This was verified by the time integrated x-ray photo-

graphs of the channel. The channel's resistance was measured by the

shift of the frequency of the ringing channel current from its zero

resistance value -- measured by replacing the wire with a 1.5 cm diam-

eter, low resistance (< 500 µΩ) conducting rod -- and by the current

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decay time. Using an average channel radius ($r \approx 1.6$ cm) allows one to estimate the channel's conductivity, $\sigma \simeq 2 \times 10^{14}$ s^{-1}, from which a temperature, $T \simeq 2$ eV, was inferred. These parameters are consistent with theory.[8] The chemical composition of the plasma channel is however unknown.

On GAMBLE I, the channel current was varied from about $\frac{1}{2}$ I_α to 2 I_α, while the anode hole (which limited the maximum injection radius) was varied from less than to greater than the channel radius. Propagation was successful only when the channel and beam currents had the same direction, in agreement with the theoretical prediction. In addition, it also became obvious that a crucial element of the experiment was the diode-channel interface. It was observed that any asymmetrical magnetic field at the target location caused a distortion in the electron distribution at the target. The inference to a similar effect at the diode-channel interface is made even more important as any current feed assymetry at the diode-channel interface could result in stray magnetic fields in the diode which could affect not only the beam injection, but also the diode physics.

Table 1 documents some GAMBLE I shots. Shown are the peak diode voltage and current; the channel current and radius (determined from the beam injection time and the plasma expansion velocity - about 0.8 mm/μs - and confirmed by visual streak photography); the next column shows r_α, the radius which enclosed the Alfvén current; the final columns show the radius of front surface damage r_D, and the radius of the back surface spall r_s.

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TABLE 1

Shot#	V(kV)	I(kA)	I_{CH}(kA)	r_{CH}(cm)	r_α(cm)	r_D(cm)	r_s(cm)
5693	700	230	80	1.6	1.1	1.1	---
5695	700	230	77	1.4	1.0	1.0	0.7
5700	800	220	68	1.6	1.2	1.2	0.9
5701	700	185	58	1.6	1.3	1.4	1.0
5903	510	205	42	1.4	1.2	1.2	0.8
5955	540	270	38	1.0	0.9	0.9	0.6

Figure 2 shows the diode voltage and current and the target x-rays for Shot 5700 on GAMBLE I. Thermoluminescent detectors allowed us to obtain an electron kinetic energy loss in the anode foil and plasma channel of 80 keV. Using this energy loss and the diode voltage gave the energy of the electrons striking the target. The collimated p-i-n detector looked at the central 3.5 mm radius of the target. From the electron energy and the p-i-n signal we calculate that at 70 ns it saw a current of 22 kA. Extrapolating the inferred current density out to the spall radius implied a propagated current of 145 kA. This is out of 195 kA of electron current in the diode (220 kA total diode current – 25 kA ion current computed using the Goldstein-Lee formula[9]) or a propagation efficiency of 74%.

On GAMBLE II, there was no parameter study done, rather the goal was to propagate a high beam current and beam current density. On four shots, calibrated x-ray p-i-n detectors indicate that more than 200 kA of electrons propagated in the channel. In addition, a fifth shot is believed to have propagated more than 200 kA based on a comparison of target damage with known shots.

On GAMBLE II, we also viewed the wire channel independently with another p-i-n detector. It indicated that an energy equivalent of less than 20 kA of electrons were lost in the plasma channel. This, however, is an upper limit as it assumed that the primary collisions occurred between the electrons and the $Z \approx 7$ plasma channel not the $Z \approx 74$ tungsten wire.

Figure 3 shows the diode voltage and current for GAMBLE II Shot 1799. In addition, the calibrated p-i-n signal is shown. Its peak signal corresponds to a current of approximately 160 kA. Since the p-i-n viewed only the center 5.3 mm radius, this indicates an average current density over this region of about 180 kA/cm^2. From the x-ray pinhole photograph, the area of the target x-rays (FWHM) was determined to be approximately 1.6 cm^2 and the total propagated current to be about 280 kA. This is out of a diode electron current of 330 kA (420 kA total diode current - 90 kA diode ion current) or an efficiency of approximately 85%. Two other shots gave propagation efficiencies over 50%, one of which had the p-i-n looking at the whole target plate and giving 255 kA.

As a final note, Figures 4 and 5 show the respective x-ray pinhole photographs for the shots described above. At the top of Figure 4 is a photograph taken with two different pinholes the lower providing greater resolution. (Since the wire itself appeared as a line source, the size of its image provided a measure of the resolution.) On the left, electrons striking the edge of the hole in the brass anode produced the annulus surrounding the x-ray image of the pinched beam passing through the titanium anode foil. In the top image, the x-rays produced by electrons in the plasma channel can be seen. The target is not seen. At the bottom of Figure 4 is a photograph taken with another pinhole camera which shows the entire system from left to right. Since the target was closer to the camera than the anode, the relative magnifications are different. On the left is

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the anode with the inner halo corresponding to an end-on view of the plasma channel. At the center of the anode is an image of the injected pinched beam while at right can be seen the image of the electrons as they strike the target. Figure 5 shows the propagation of electrons for GAMBLE II Shot 1799. The circular ring around the target is pinhole shine-through while the crosshairs used for alignment are seen as an absence of exposure.

III. THEORETICAL CONSIDERATIONS:

The problem of relativistic electron flow in plasmas heated before beam injection has been treated at length in the literature.[10] Most of the treatments were concerned with the plasma current response to the injected beam current. Two effects were neglected.

First, the conducting plasma has a finite radius, outside of which there exist only low conductivity, cool air (theoretical models assumed high conductivity at all radii) and thus the total return current is forced to run in the conducting plasma due to the voltage increase on the target for the relativistic electron beam – this electrostatic effect was not included in previous theoretical work which included inductive effects only. The fact that the return current is forced to run in the plasma also explains why the $\dot{B}_\theta$ loop placed outside the plasma (in both our and the Sandia experiments) showed essentially zero current change during beam transport. There may be about 0.1% of the primary beam current going through the capacitor bank and the return current rods connected to the anode plane of the generator[11] but this is too small a current to be detected with the $\dot{B}_\theta$ loop in the present experiments.

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Second, the hydrodynamics of the plasma has not received proper treatment. Usually magnetic fields are viewed as confining fields because of the pressure tensor. In the case of beam injection into a plasma however, while the beam particles are confined by the magnetic field, the plasma is pushed outwards. The reason is that the return current set up in response to the injected beam is negative so that the $\mathbf{j}_{plasma} \times \mathbf{B}$ force is pushing the plasma out. Note that $\mathbf{j}_{plasma} \simeq -\mathbf{j}_{beam}$. We give below a simple calculation that shows when plasma expansion becomes a significant process. The main effects of this is an increase in the channel radius with its concurrent reduction of the magnetic field and thus the radial expansion of the hot e-beam. The radial expansion is:

$$\ell_{exp} \simeq \frac{1}{2} \left(\frac{\mathbf{j} \times \mathbf{B}}{\rho c} \right) \tau^2 \simeq \frac{I_B I_{CH}}{\pi r^3 \rho} \tau^2 \times 10^{-12} \qquad (3)$$

where the beam and channel currents are given in kA, beam pulse time in 10^{-8} sec, plasma radius (which is also assumed to be the beam radius) in cm, and the plasma mass density in g/cm^3. For the case of our GAMBLE II experiments $I_B \simeq 280$ kA; $I_{CH} \simeq 50$ kA; $\rho \simeq 10^{-4}$ g/cm^3; and $\tau \simeq 5 \times 10^{-8}$ sec we find that the plasma expands less than 10^{-2} cm. If, on the other hand, we had tried to propagate the same beam with a radius of 0.1 cm, the plasma expansion after 50 ns would be many times the initial radius which indicates that plasma MHD effects would start to dominate.

We thus conclude that the present experiments in open air were performed at a high density with little hydrodynamic effects during

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the beam propagation while Physics International experiments[5] with
tapered Z-pinches and low densities ($\rho \simeq 10^{-7}$ g/cm^3) were strongly
affected by such effects.

We now point out some limitations on current propagation. The
simplest limit is that due to the plasma conductivity. An electric
field $\underset{\sim}{E} = \underset{\sim}{J}_{beam}/\sigma_{plasma}$ is needed to drive $\underset{\sim}{J}_{return} \simeq \underset{\sim}{J}_{beam}$. An upper
limit on this field for our GAMBLE II experiment is

$$\underset{\sim}{E} = \frac{2.80 \times 10^5 \cdot \frac{c}{10}}{\pi(1.6)^2 2 \times 10^{14}} \cdot 3 \times 10^4 \simeq 16 \text{ kV/m}$$

We now consider the question of magnetic field diffusion and its effect
on electron beam trajectories.

Because of finite channel conductivity the magnetic field profile
will change. The time scale for change over a length r in the radial
direction is given by

$$\tau = \frac{4\pi\sigma r^2}{c^2}$$

For a length scale of $r = 0.5$ cm, and plasma conductivity of
$\sigma = 2 \times 10^{14}$ sec^{-1}, $\tau = 750$ ns. The plasma temperature of 2 eV is
obtained via the heating by the discharge current of 50 kA during 20 μs;
very little additional heating is expected due to the 10^5 A/cm^2 primary
current for the plasma densities (10^{19} cm^{-3}) in the experiment. During
a 100 ns pulse the net current will increase by $\Delta I = I_{beam}(1-e^{-\frac{100}{750}}) =$
0.15 I_b which gives $\Delta I = 30$ kA for $I_{beam} = 200$ kA. The increased mag-
netic field due to the net current drastically affects the electron
orbits. If the beam radius at injection is nearly equal to the plasma

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channel radius, the relativistic electrons injected at large angles will
be returned back to the diode by this magnetic field and the efficiency
of propagation will be reduced. If, however, the beam radius was
initially smaller than the channel radius then the electrons will
expand radially to fill a radius smaller than the channel radius which
encloses the Alfvén current. As the net current increases, this radius
will decrease and the beam will propagate at a higher current density.
For this case, no reduction in efficiency will be observed. This effect
should be more pronounced at higher total beam currents. The experiments
on GI, Hydra (at SLA) and GII are characterized by beam currents of 100,
200 and 250 kA accordingly. In view of the above discussion one should
observe the tightest pinches propagated on GII as was indeed observed.
If one tries to extrapolate into beam currents of a few mega-amperes
then the magnetic field diffusion will be too large and extend into radii
less than the beam injection radius causing a reduction of efficiency of
transport.

We turn now to the effect of time variation of diode voltage. Since
a channel current nearly equal to I_α is needed for transport, when diode
voltage is reduced the needed current is accordingly reduced. The com-
bination of initial channel current and the increase of the current by
magnetic diffusion bring the total current above I_α as diode voltage
falls. This is one of the reasons why GI or Hydra which had nearly
constant voltage pulses, show almost constant efficiency of transport
while fast changing impedance experiments on GII showed a drastic re-
duction of beam transport efficiency during the 50 ns pulse.

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Based on all the preceding discussion we may now put limits on the total current that can be transported using the present technique. First, the conductivity defines an electric field by $j = \sigma E$, which cannot exceed the diode voltage divided by the channel length.

$$ J < \sigma \cdot \frac{V}{\ell} = \sigma \frac{V_{MV}}{\ell_m} \times 10^{-8} \left(\frac{A}{cm^2} \right) $$

for $V = 1$ MV, $\sigma = 2 \times 10^{14}$, $\ell = 1$ meter

$$ J < 2 \times 10^{10} \frac{A}{m^2} = 2 \times 10^6 \ A/cm^2 \ . $$

For a distance of 10 meters only $2 \times 10^5 \ A/cm^2$ can be transported in these channels, however at higher current densities, these estimates will be modified by the higher temperatures and conductivities associated with the primary and return-current heating.

Second, the plasma channel expansion limits the tightness of the transported beam. For example if we take the 2 MA/cm^2 beam of 1 MV electrons discussed above and inject them into a 5 mm radius air channel carrying the Alfvén current, the channel radius will double in 50 ns. Even taking the magnetic diffusion into account the Alfvén radius will still be 1.2 times the original channel radius.

IV. CONCLUSIONS

In summary we have shown experimentally that high power density electron beams may be efficiently transported using these current-carrying air plasma channels. We have shown theoretically that certain restrictions apply to their use - the most restrictive being the limitation on the current density. This restriction may be overcome to a

certain extent by increasing the channel temperature. This might be accomplished by using a lighter background gas.

The self-consistent problem of plasma-channel expansion occurring simultaneously with the magnetic diffusion and its ultimate effect on the transported beam and the transport efficiency must still be studied.
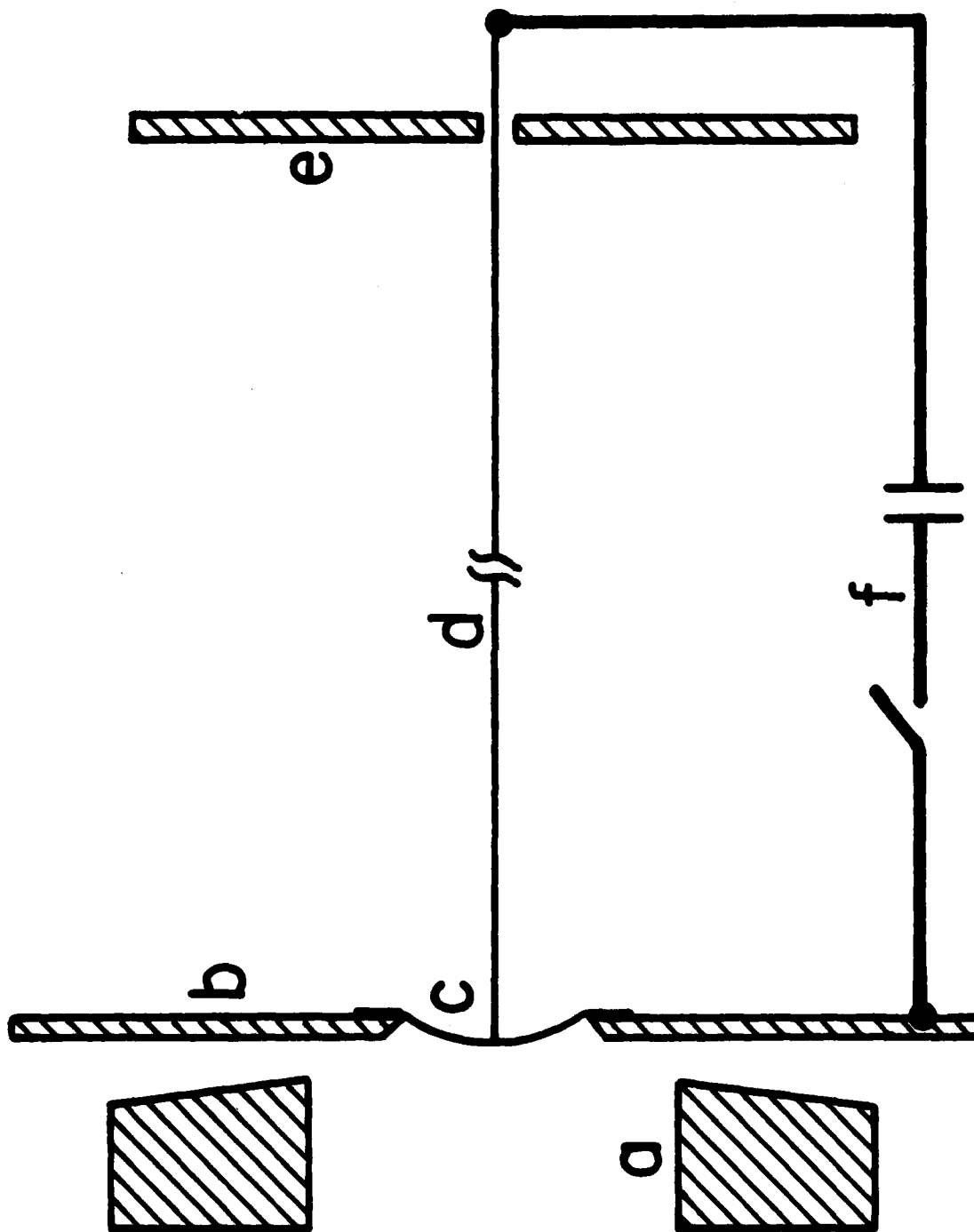
Fig. 1 — This schematic of the experimental apparatus shows: a) the brass cathode; b) the brass anode; c) the titanium/aluminum foils; d) the wire; e) the aluminum target; and f) the switch and capacitor bank which supplies the channel current.

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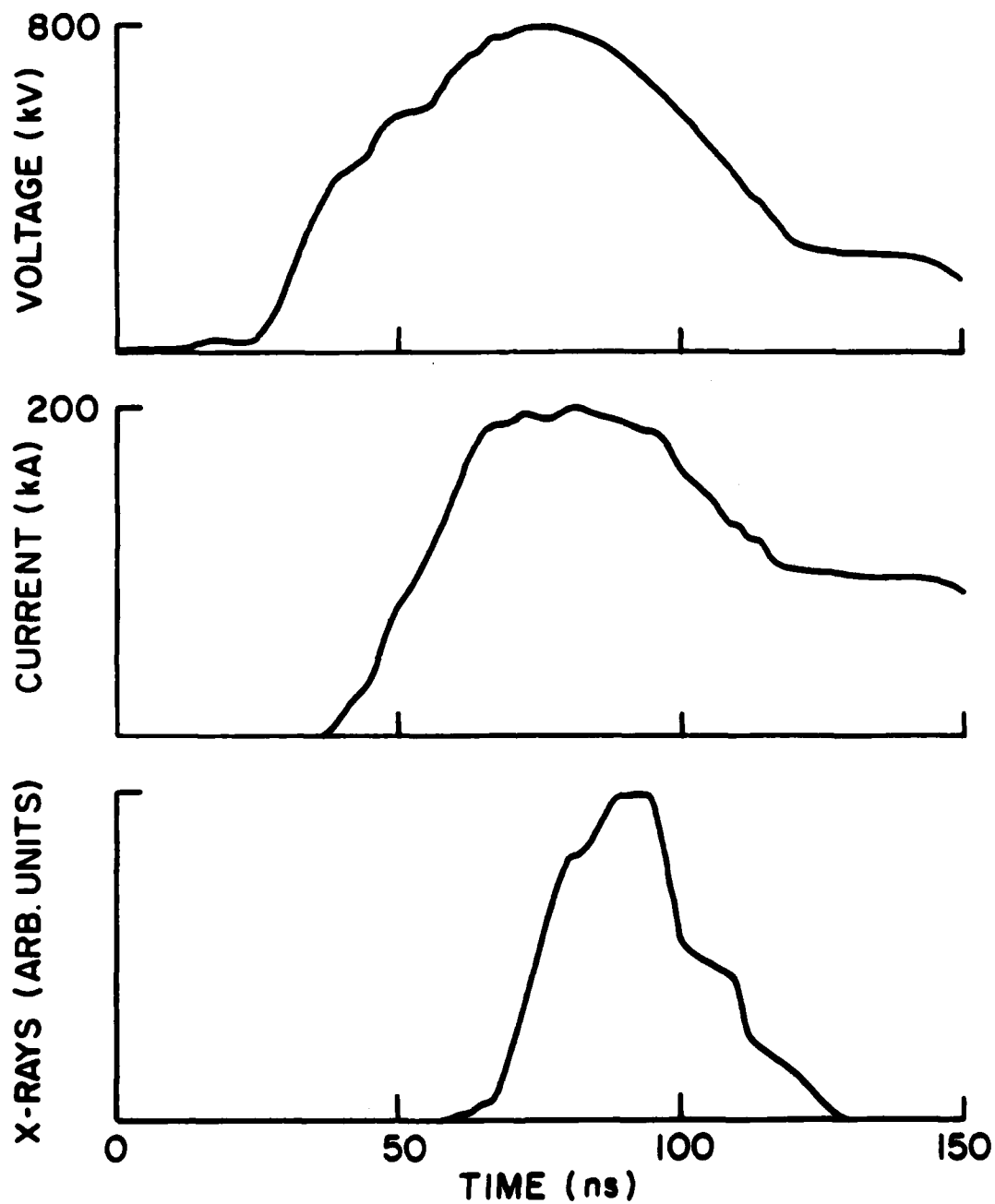
Fig. 2 — Diode voltage, current, and x-rays for GAMBLE I shot 5700.
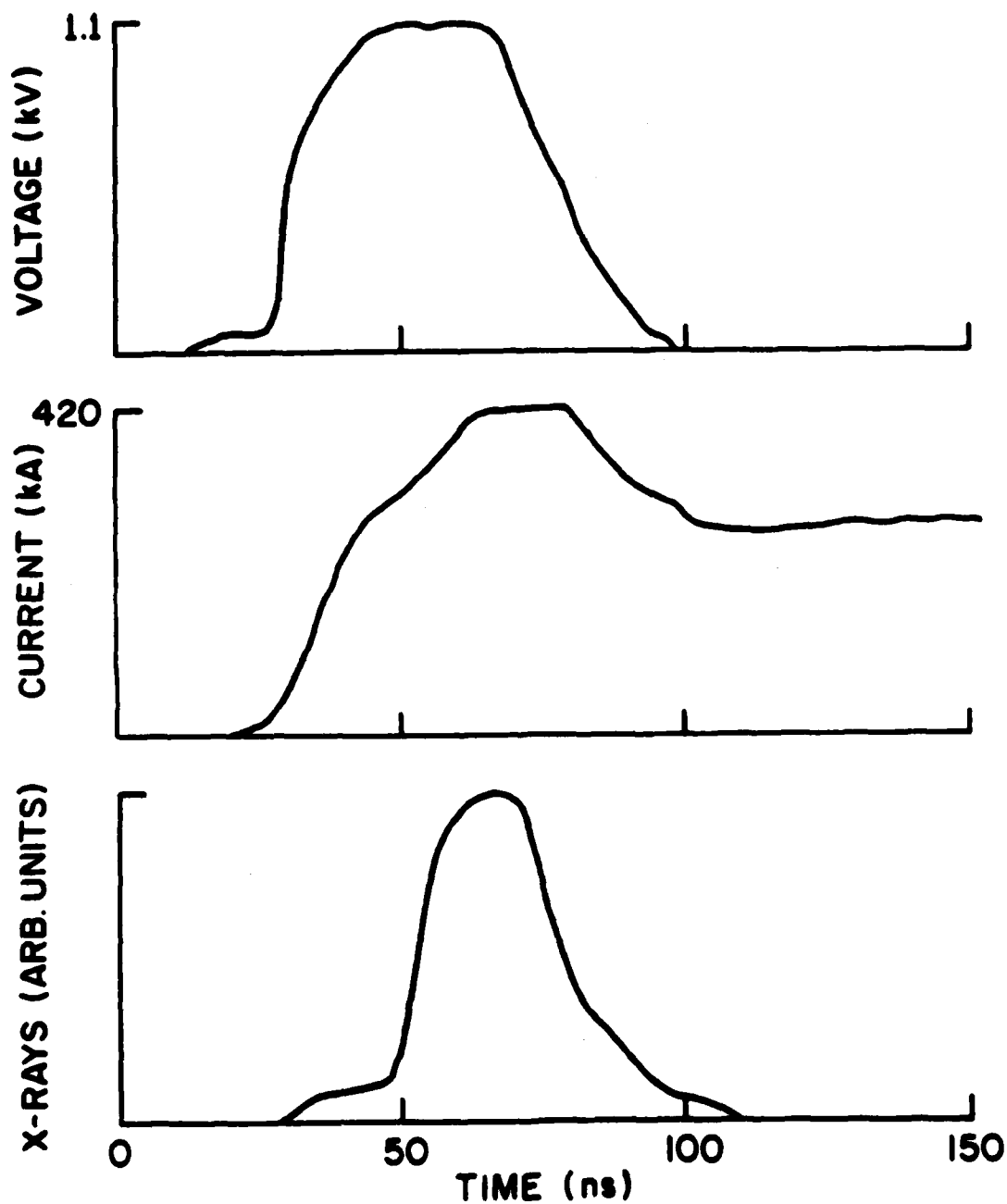
Fig. 3 — Diode voltage, current, and x-rays for GAMBLE II shot 1799.
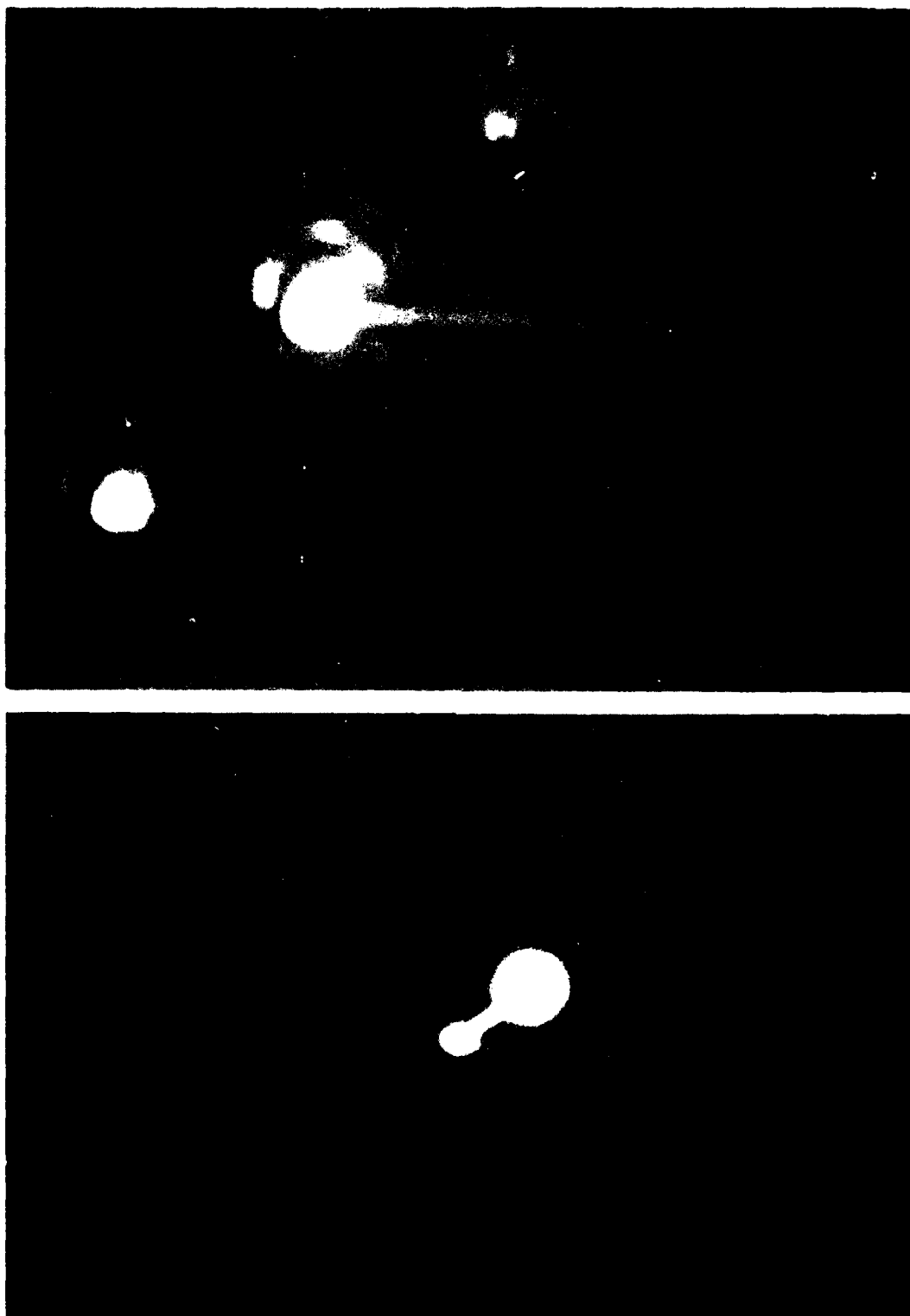
Fig. 4 — X-ray pinhole photographs for Gamble I shot 5700.
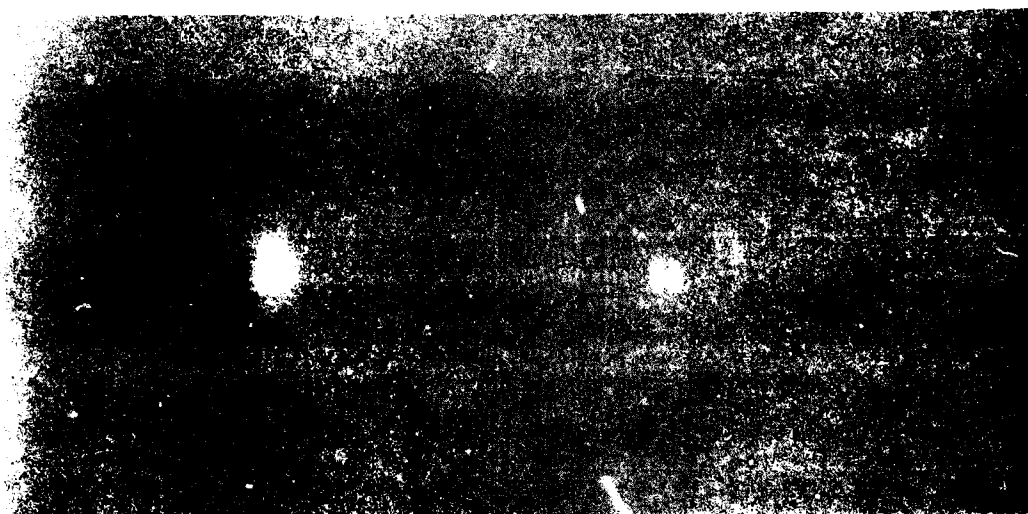
Fig. 5 — X-ray pinhole photograph for GAMBLE II shot 1799.

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